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14. ABSTRACT
This report describes the research performed on behalf of the Office of Naval Research (grant # N00014-01-D-0043 Delivery Order 0006) on the following: The enhanced operation of offboard active surveillance and communications systems has been demonstrated through the use of phase conjugation (time reversal) techniques to enhance echo-to-reverberation-ratio in active sonars and mitigate multipath in acoustic data communications.

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Offboard Active Surveillance and Communications

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Offboard Active Surveillance and Communications

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Abstract

The enhanced operation of offboard active surveillance and communication systems has been demonstrated through the use of phase conjugation (time reversal) techniques to enhance echo-to-reverberation-ratio in active sonars and mitigate multipath in acoustic data communications.

Research Summary

A phase conjugate "mirror" time reverses the incident signal precisely returning it to its original source location. This phenomenon occurs independent of the complexity of the medium. The time-reversal process can be accomplished by the implementation of a retransmission procedure. A signal received at an array is time reversed and retransmitted. A full water column source array excited by the phase conjugated (time-reversed) signal received at the array position will focus at the position of the radiating target. The medium fluctuations are embedded in the received signal so that if retransmission can occur on a time scale less than the dominant fluctuations, the medium variability will be eliminated since one back propagates and "undoes" the variability.

Two low frequency (~450 Hz) phase conjugation field experiments previously were carried out (FY96 and FY97) in ~125 m water adjacent to Formiche di Grosseto (a small island approximately 100 miles SW of NURC). These experiments demonstrated that phase conjugation is both feasible and stable at low frequencies in shallow water and that focusing of the retransmitted energy is possible at ranges of at least 30 km. Also demonstrated was the ability to shift the range of focus to ranges other than that of the probe source by a simple method involving a frequency shift of the received time series prior to retransmission. Lastly, the degradation of focusing with fewer than the full set of source/receive array (SRA) transducers was investigated and reasonable focusing was demonstrated with as few as 6 SRA transducers at a range of 15 km. Results from the April 1996 and May 1997 experiments appear in [1-4,6].

As an outgrowth of the successful low frequency phase conjugation experiments, ONR sponsored two high frequency (~3.5 kHz) phase conjugation (HFPC) experiments which were carried out with NURC in FY99 and FY00. Central to these experiments was a new high frequency vertical array of 29 source/receive transducers operating nominally in the 3-4

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kHz band, an underwater pressure case containing the source/receive electronics, and a surface buoy providing battery power, system control, and wireless local area network (WLAN) connectivity [19]. These experiments demonstrated that high frequency phase conjugation also is feasible with focusing at ranges out to 21 km in both flat (~125 m deep water) and sloping (~125 m deep water shoaling to ~40 m deep water) coastal environments. Also measured was the stability of the focal region (observed to be on the order of 30 min). Lastly, the use of phase conjugation processing in both active target detection and acoustic communications was demonstrated. Both (artificial) target echo enhancement and reverberation reduction through time reversal focusing were shown feasible as well as the use of phase conjugation processing in acoustic communications with the transmission of BPSK and QPSK sequences over a 10 km range. Results from the July 1999 and May-June 2000 experiments appear in [6, 8-11,14, 20-24, 29-31].

Subsequently, two recent Focused Acoustic Fields (FAF) experiments have been carried out with NURC in FY03 and FY04. The FAF-03 experiment took place in March-April 2003 north of Elba Island, Italy. In addition to carrying out time reversal focusing at 3.5 kHz, the 29-element HFPCA source/receive array hardware [19] was modified to enable operation at ~850 Hz. The accomplishments of FAF-03 included demonstrating the following (at both 850 and 3.5 kHz unless otherwise indicated): (1) successful operation of a new source/receive transducer array (850 Hz), (2) time reversal focusing in Winter/Spring sound speed profiles, (3) a new focusing procedure which facilitates time reversal focusing without requiring deployment of a probe source but instead uses one or more radio-telemetered receiving transducers, (4) simultaneous and sequential focusing at multiple depths, (5) multiple-depth (simultaneous) and synthetic aperture time reversal acoustic communications (3.5 kHz), and (6) reverberation nulling without explicit use of a probe source.

The FAF-04 experiment was carried out with NURC in July 2004 north and south of Elba Island, Italy. The accomplishments of FAF-04 included the following at 3.5 kHz: (1) further demonstration of simultaneous and sequential focusing at multiple depths using only a receiving element/array with radio link feedback instead of an active probe source, (2) multiple-depth (simultaneous) and synthetic aperture time reversal acoustic communications, (3) passive time reversal acoustic communications from a mobile source (AUV), (4) echo-to-reverberation enhancement via (artificial) target focusing, (5) reverberation nulling without explicit use of a probe source, and (6) successful deployment and demonstration of focusing with a billboard source/receive array (SRA).

Results from the March-April 2003 and July 2004 experiments appear in [12-13, 15-18, 25-29].

Examples of Research Results

The potential for reducing reverberation through time-reversal focusing was investigated in FAF-00 by carrying out the focusing procedure shown in Fig. 1 along with recording the backscatter (reverberation) received by the SRA after the retransmission [11]. A probe source (PS) collocated with the vertical receive array (VRA) ensonified the waveguide. The dispersed pulse with all its multipath structure was received by the source/receive array

(SRA), time-reversed, and retransmitted by the same transducers. The extent to which the retransmitted energy refocused at the PS (as observed by the VRA) is a measure of the ability to carry out phase conjugation processing. In addition, since the energy is focusing at the PS, less energy is scattered from the surface and bottom.

As an illustration, Fig. 1 compares the power received by the VRA at 4.7 km range from both time-reversal focusing of a 100 ms PS pulse at 60 m depth and a simple broadside transmission (no time-reversal) of a 100 ms pulse by the SRA. Fig. 2 shows the power observed on each element of the SRA for 8 sec after transmission along with the time series of instantaneous power from a single (mid-array) element. The dip in the time-reversal return at ~6.3 sec corresponds to the range of the PS thus demonstrating that focusing the SRA transmission mid-water column leads to a reduction in the returning reverberation from this range.

During FAF-03, a new focusing procedure was implemented which did not require deployment of a separate probe source [12]. Instead, a radio-telemetered vertical receive array (VRA) effectively provided the equivalent waveguide impulse response required for time reversal. The procedure is illustrated in Fig. 3. By reciprocity, the impulse response from a probe source to the source-receive array (SRA) can be obtained by a single element of the VRA at the probe source location receiving pings from each element of the SRA transmitted sequentially. The multiplexed reception at the VRA element is made available via radio telemetry. After demultiplexing, the multiple impulse responses (one for each SRA element) are time reversed and retransmitted by the SRA yielding a focus at the equivalent probe source location. This procedure then can be generalized to focus SRA transmissions either sequentially or simultaneously at any of the depths of the VRA elements.

Fousing at multiple depths was demonstrated during FAF-03 at both 850 Hz and 3.5 kHz in 105 m deep water with a 8.6 km separation between the SRA and VRA. Fig. 4 shows examples of 3.5 kHz focusing both sequentially at all 32 depths of the VRA elements and simultaneously at 6 depths across the water column.

The simultaneous transmission of acoustic communications sequences to multiple depths also was demonstrated during FAF-03 at 3.5 kHz in 105 m deep water with an 8.6 km separation between the SRA and VRA [15]. Fig. 5 shows an example of focusing QPSK transmissions at three different depths. Fig. 6 shows the resulting symbol scatter plots indicating low bit error rate.

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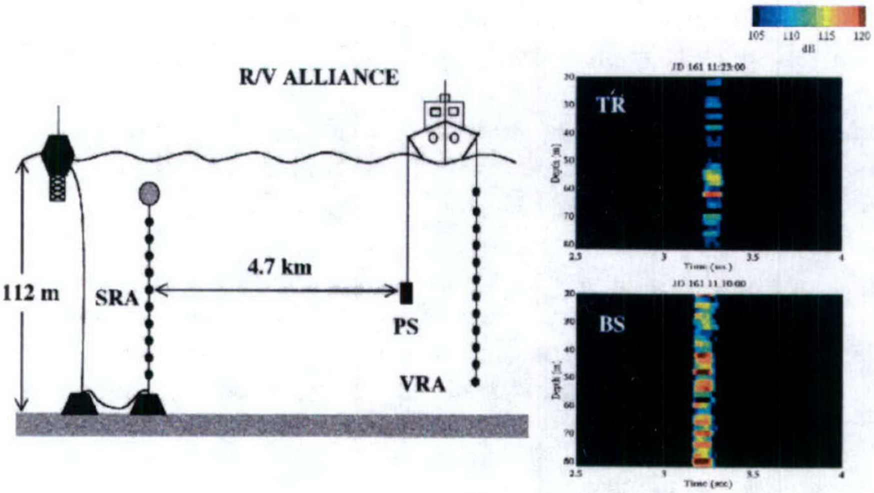

Figure 1. Comparison of the power received by the VRA at 4.7 km range from both time-reversal focusing of a 100 ms PS pulse at 60 m depth and a simple broadside transmission of a 100 ms pulse by the SRA which results in the pulse being spread across the entire water column at the VRA.

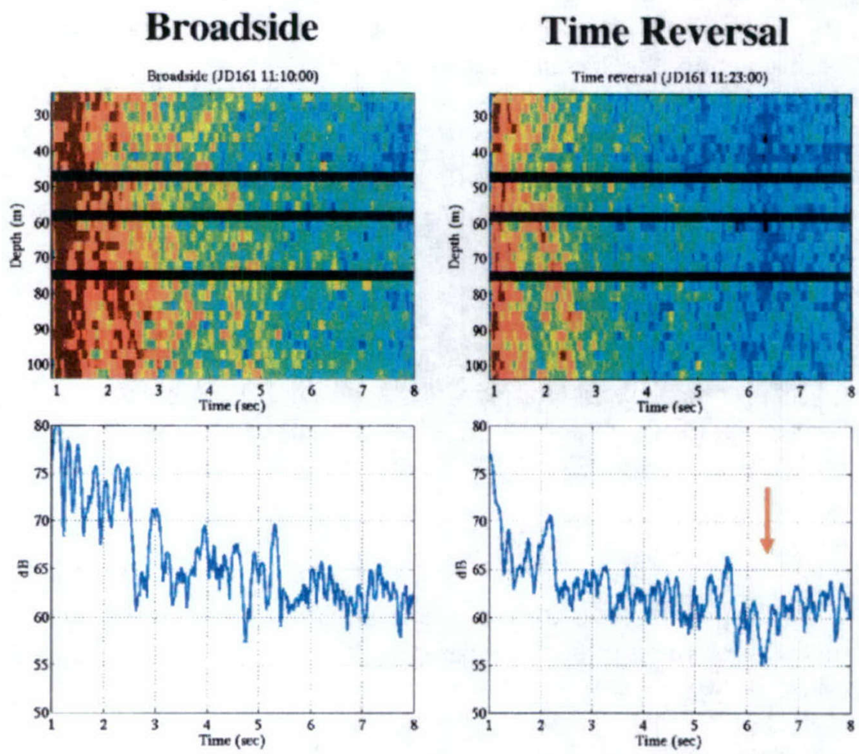

Figure 2. The reverberation observed on each element of the SRA for 8 sec after transmission and that from a single (mid-array) element. The dip in the time-reversal return at ~6.3 sec corresponds to the range of the PS.

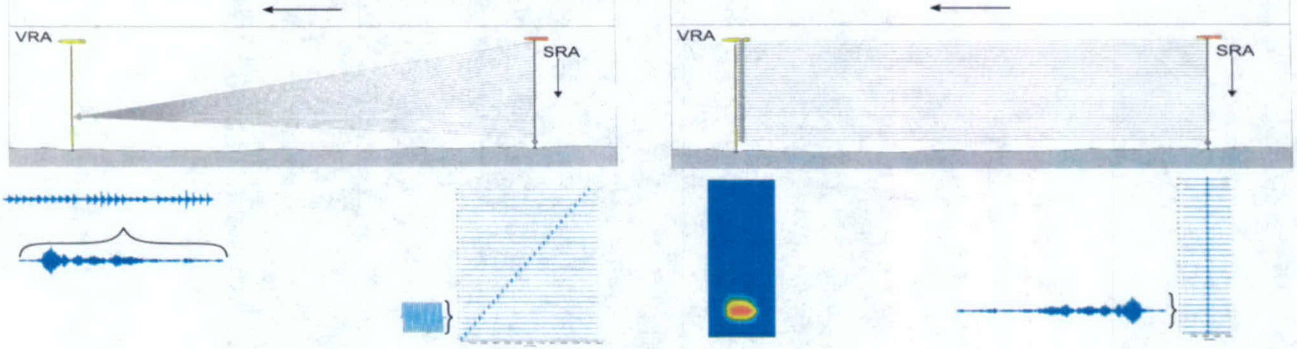

Figure 3. Illustration of the new focusing procedure. (a) Transmit pings sequentially from each element of the source-receive array (SRA). Receive these transmissions at a single element of the vertical receive array (VRA). Make available the multiplexed reception at the VRA element via radio telemetry. (b) After demultiplexing, time reverse and retransmit simultaneously from the SRA the multiple waveguide impulse responses (one for each SRA element). The retransmission focuses at the VRA element from which the impulse responses were extracted.

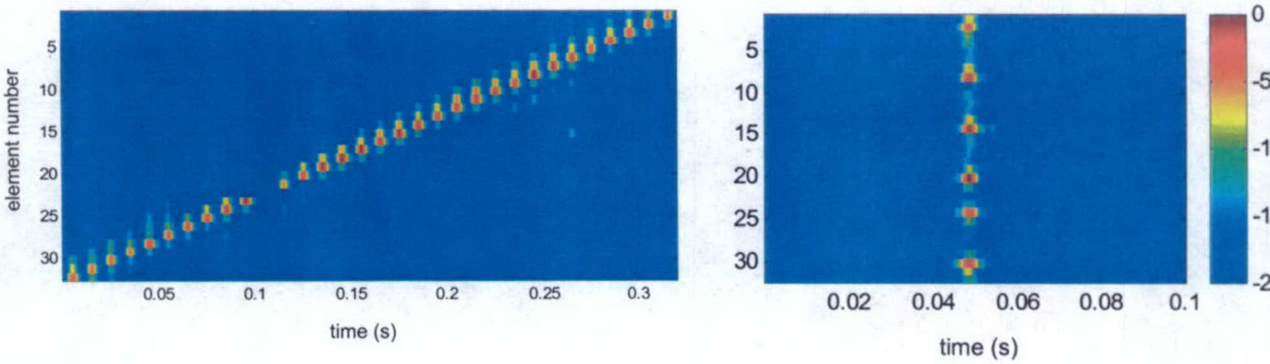

Figure 4. Focusing at 3.5 kHz and multiple depths during FAF-03 using the new focusing procedure. The SRA and VRA were separated by 8.6 km in 105 m deep water. The panels show the reception from all 32 elements of the VRA (elements are numbered from closest to seafloor to closest to sea surface). (a) Sequential focusing at all 32 elements. (b) Simultaneous focusing at 6 depths across the water column.

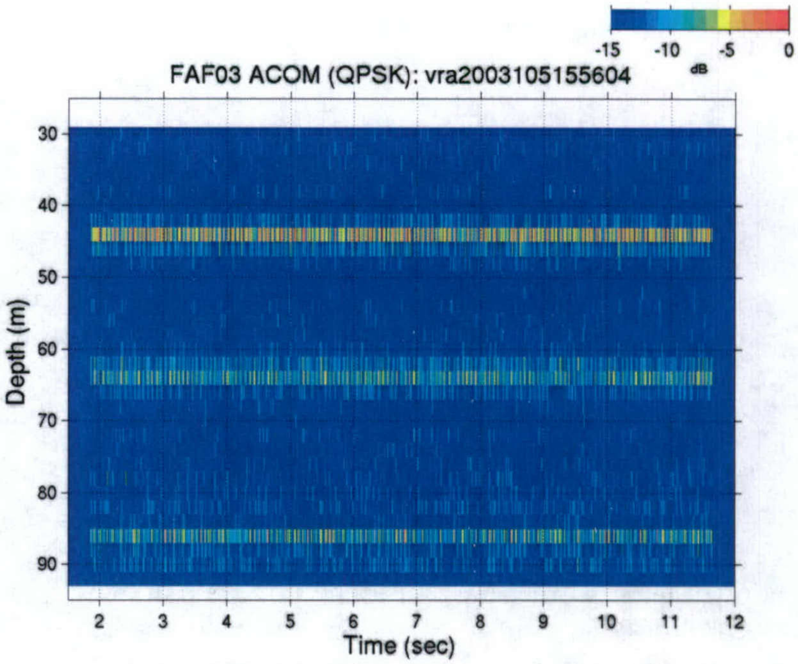

Figure 5. During FAF-03, acoustic communication sequences also were transmitted simultaneously to three depths at 3.5 kHz in 105 m deep water with an 8.6 km separation between the SRA and VRA.

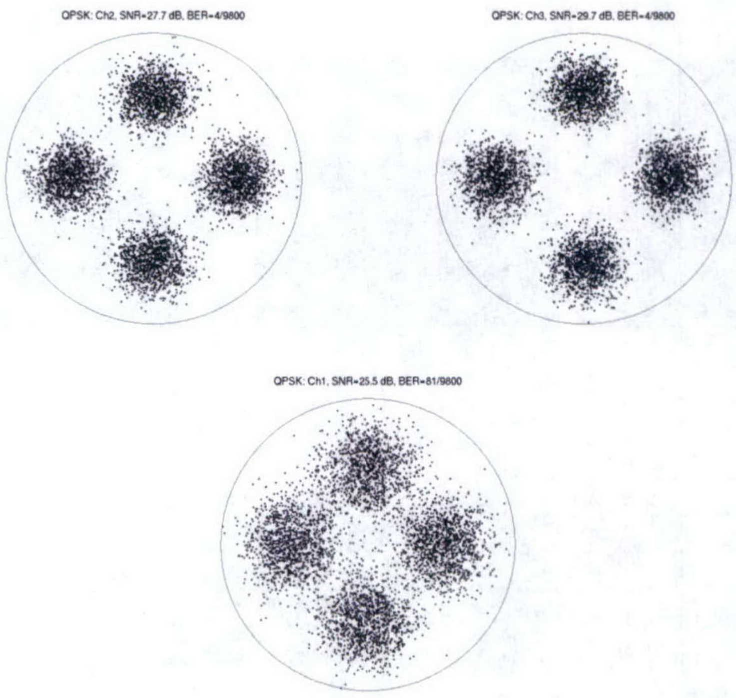

Figure 6. The resulting QPSK symbol scatter plots indicate low bit error rate.